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# ERDA/NASA 100-KILOWATT MOD-0 WIND TURBINE OPERATIONS AND PERFORMANCE

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16. Abstract

The ERDA/NASA 100 kW Mod-0 wind turbine became operational in September 1975 at the NASA Plum Brook Station near Sandusky, Ohio. The operation of the wind turbine has been fully demonstrated and includes start-up, synchronization to the utility network, blade pitch control for control of power and speed, and shut-down. Also, fully automatic operation has been demonstrated by use of a remote control panel, 50 miles from the site, similar to what a utility dispatcher might use. This report briefly describes the operation systems and experience with the wind turbine loads, electrical power and aerodynamic performance obtained from testing.

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E-9403

## SUMMARY

The objective of the Federal Wind Energy Program, under the direction of the Energy Research and Development Administration (ERDA), is to advance the technology and accelerate the development and utilization of reliable and economically viable wind energy systems. As a part of this program, the NASA Lewis Research Center (LeRC) was delegated by ERDA to design, build and test a 100 kW wind turbine at the NASA Plum Brook Station near Sandusky, Ohio. The purpose of this wind turbine was to provide early operations and performance data of a large wind turbine, in various configurations, to aid in the design of follow-on large wind turbines. The 100 kW wind turbine was designed, built and assembled in 18 months and became operational in September 1975. The wind turbine consists of a two bladed 125-foot diameter down-wind rotor operating at 40 rpm and driving a synchronous alternator at 1800 rpm through a step-up gear box. The wind turbine is kept aligned with the wind direction by a yaw control and the rotor speed and power is controlled by blade pitch control. The entire rotor, drive train assembly and yaw control are located in a nacelle 100 feet above ground on top of a steel truss tower. Operation of the 100 kW wind turbine has been fully demonstrated and includes startup, synchronization to the utility network, blade pitch control for control of power and speed, and shutdown. Also fully automatic operation has been demonstrated by use of a remote control panel, 50 miles from the site, similar to what a utility dispatcher might use. This report briefly describes the operation systems and experience with the wind turbine and the loads, electrical power and aerodynamic performance obtained from testing.

## INTRODUCTION

The Federal Wind Program was initiated in 1973 as a part of the nation's solar energy program. The first wind energy workshop was held in 1973 (Ref. 1) to review past work in wind energy and to assess the potential of wind power. From this workshop it became evident that it was desirable to test a representative large wind turbine as quickly as possible to provide engineering data for use as a base for the entire wind energy program. During FY 1974 a 5 year wind energy program plan was developed as part of the Solar Energy Plan of the Project Independence Blueprint (Ref. 2). This wind energy program included the 1973 workshop recommendation to proceed with the design, building and testing of a nominal 100 kW, 125 foot diameter rotor wind turbine; this wind turbine was designated Mod-0.

The NASA Lewis Research Center (LeRC) was delegated the responsibility for designing, building and testing the Mod-0 wind turbine as part of the wind energy program being managed by National Science Foundation. In January 1975 the responsibility for managing the wind energy program was transferred to the recently formed Energy Research and Development Administration (ERDA). NASA-LeRC has continued to manage the Mod-0 project and several other large wind turbine projects under the overall program management of ERDA.

The Mod-0 wind turbine is located on a site near Sandusky, Ohio and first became operational in September 1975. This paper briefly describes the Mod-0 wind turbine and reports on the control and safety systems for normal operation, results of operations experience and performance data obtained from testing.

## DESCRIPTION OF MOD-0 WIND TURBINE

The Mod-0 wind turbine has been described in several earlier reports (refs. 3 to 8). Figure 1 shows a line drawing of the Mod-0 wind turbine and Figure 2 is a photograph of the wind turbine in operation at the NASA Plum Brook site near Sandusky, Ohio. The wind turbine has a 2-bladed constant 40 rpm 125-foot diameter rotor located downwind of the tower. The rotor drives a 100 kW synchronous alternator through a step-up gear box. The drive train and rotor are located in a nacelle with a centerline 100 feet above ground. The nacelle sits on top of a 4-legged steel truss tower. Wind direction is sensed by a wind vane on top of the nacelle and is used as a signal for the yaw control for keeping the wind turbine aligned in the direction of the wind. Details of the drive train system and the yaw system are shown in figure 3. Figure 4a is a photograph showing the drive train and yaw drive assembled and undergoing testing prior to shipment and installation at Plum Brook. Figure 4b shows the drive train and yaw system with the nacelle being checked out at Plum Brook prior to assembly of the blades and installation on top of the tower. The wind turbine including the yaw drive, drive train and rotor blades was lifted to the top of the tower in one operation as shown in figure 5.

## OPERATION

The operation of the Mod-0 wind turbine consists primarily of startup, normal operations connected to the utility network, shutdown and standby. Figure 6 shows the several different modes that Mod-0 can be operated in at Plum Brook. In addition to connection to the Ohio Edison utility system, Mod-0 can be connected to: 1) a load bank; 2) a diesel generator of approximately 160 kW; and 3) the Plum Brook network. The Plum Brook network can be disconnected from Ohio Edison to provide a good simulation of a small utility network with several small generators and real load characteristics.

The basic wind turbine controls are: 1) the yaw control for aligning the wind turbine with the wind direction; and 2) the blade pitch control used for startup, shutdown and power control. All normal operation functions are programmed into a microprocessor which provides the supervisory control for the wind turbine. A safety shutdown system is wired into the Mod-0 controls to automatically and safely shut the wind turbine down in the event any key parameters are out-of-tolerance. In addition to the on-site microprocessor and safety systems, a remote control and monitoring system is designed to allow the Wind Energy Project Office (or a local utility dispatcher in the case of follow-on wind turbines) to monitor and control the wind turbine operation.

## Normal Control

When the wind turbine is shutdown the blades are feathered and are free to slowly rotate. The normal wind turbine operation for cut-in, rated and cut-out wind speeds is shown in figure 7. Gilbert describes the normal startup, shutdown and overspeed conditions in reference 7. For wind speed at cut-in (10 mph) or greater, the yaw control is activated and the wind turbine aligned with the wind. The blades are then pitched at a programmed rate and the rotor speed is brought to about 41 rpm. At this time the automatic synchronizer is activated and the wind turbine is synchronized with the utility network. Synchronization analyses for the Mod-0 are reported in reference 9.

For wind speeds between cut-in and rated (18 mph) the blade pitch angle is held constant at $0^o$ (at 3/4 of the blade radius). For wind speeds above rated the blade pitch angle is automatically controlled to limit the wind turbine power to 100 kW. For winds above cut-out (40 mph), the blades are feathered and the wind turbine is shutdown. The yaw control, hydraulic systems and electrical systems are all turned off when the wind turbine is shutdown.

## Microprocessor

For utility operation, it is planned that the wind turbines will be located some distance from the control power station or the dispatcher's control room. It is further planned that the wind turbine operation be completely automatic and that the wind turbine will deliver power to the network whenever the wind speeds are between cut-in and cut-out.

To accomplish this, the control logic for achieving proper startup, synchronization, power control, and shutdown is all contained in a supervisory control system utilizing a microprocessor. The microprocessor is located at the wind turbine site with the other electrical controls and is programmed to automatically execute all the normal wind turbine operation and control sequences. For example, the microprocessor tracks the wind speed and initiates the startup sequence when wind speed reaches cut-in and shutdown when the wind speed goes above cut-out.

## Safety Shutdown System

The safety shutdown system for Mod-0 is an emergency shutdown system which operates independently of all other wind turbine controls. The safety system uses a set of sensors to monitor potential problem areas to protect the wind turbine from a catastrophic failure. These sensors monitor key parameters such as: rotor overspeed, overcurrent or reverse current, vibration, yaw error, pitch system hydraulic fluid level, key temperatures and microprocessor failure. If any sensor detects an out-of-tolerance signal the safety system initiates shutdown of the wind turbine. Critical sensors and circuits such as those for monitoring speed are redundant. A failure of the safety system will also initiate a shutdown.

## Remote Control and Monitoring System

A simple remote control and monitoring system (RC&M) is incorporated in the Mod-0 system. The RC&M is located at the Lewis Research Center, 50 miles from Plum Brook, and is connected to the wind turbine by a dedicated telephone line. The RC&M provides a means of remotely controlling and monitoring the Mod-0 operation. The RC&M shown in figure 8 is the same control system planned for use on the Mod-0A wind turbines which are all scheduled for utility operation. The RC&M provides the remote operator (utility dispatcher) with a start and stop mode, up to 8 channels of analog signals and key discrete signals that can shut the wind turbine down.

## Operations Summary

The Mod-0 operations to date have shown that the wind turbine basic controls for speed, power and yaw work satisfactorily. Synchronization to the utility network has been demonstrated routinely. The normal wind turbine operations for startup, utility operation, shutdown and standby have all been demonstrated and performance is quite satisfactory. The Mod-0 has also been used to check out remote operation planned for follow-on Mod-0A and Mod-1 wind turbines. In summary, the Mod-0 has exhibited quite satisfactory operation and no operations problems are apparent at this time.

# PERFORMANCE

The purpose of this section is to summarize the performance information that has been obtained from Mod-0 testing. Three areas of performance are discussed: (1) blade dynamic loads; (2) power system dynamics in the drive train when the WT is synchronized to the utility network; and (3) the aerodynamic performance of the wind turbine.

## Dynamic Loads

The Mod-0 first achieved rated speed and power in December 1975. At this time, the machine performed as predicted except for larger than expected blade bending moments (ref. 10).

These blade loads were higher than expected for both the flatwise (out-of-plane) and edgewise (in-plane) moment loads. These high loads did not damage the blades, but continuous operation at these load levels would have resulted in early fatigue failure of the blades. Figure 9 shows the predicted blade loads, both flatwise and edgewise, and the December 1975 data as reported by Spera (ref. 11). The predicted loads were obtained using the MOSTAB rotor analysis code (ref. 12). The cyclic mements plotted in figure 9 are at station 40 in the blade shank (40 in. from the rotor axis) and are plotted versus nominal wind speed. Cyclic moment is equal to one-half the difference between the maximum and minimum values of moment during one revolution of the rotor. The data is represented by mean values with the bars representing $\pm 1\sigma$ ($\pm$ 34 percent of the data about the mean). The variations about the mean are caused by such things as variations in wind direction and velocity and control changes.

As a result of the high blade loads, an intensive study was undertaken to analyze the loads data and to (1) determine the causes of the high loads and (2) to recommend modifications to reduce the loads. This study clearly showed that the flatwise bending moments were primarily caused by the impulse applied to the blade each time it passed through the wake of the tower. It was concluded that the tower was blocking the airflow much more than had been expected. The higher blockage was confirmed by site wind measurements (ref. 13) and wind tunnel tower model tests (ref. 14). To reduce the tower blockage and increase the airflow through the tower it was decided to remove the stairways from the tower. Figure 10 shows the tower with and without stairs. This modification reduced the tower blockage from 0.64 to 0.35 (a blockage of 1.0 meaning that the airflow through the tower is zero).

The study of the edgewise blade loads, particularly their harmonic content, led to the conclusion that these high loads were caused by excessive nacelle yawing motion. To reduce these loads it was recommended that the single yaw drive be replaced by a dual yaw drive. This dual yaw drive was expected to help by (1) changing the torsional frequency of the system and moving it away from the 2P (two cycles per rotor revolution) resonance; and (2) eliminating the free-play present in the single yaw drive. Figure 11a shows the dual yaw drive that was implemented on Mod-0. In addition to the dual yaw it was also decided to add three brakes to the yaw system to provide additional stiffness (fig. 11b). The result of these modifications on the blade moments is shown in figure 12. Both flatwise and edgewise bending moments were reduced below the values predicted by MOSTAB.

It should be noted that tower shadow and yaw stiffness are excellent examples of why the Mod-0 project was initiated. The early higher than expected loads led to extensive re-evaluation of the analytical tools and subsequent redesign of the wind turbine. This information has been extremely important in the design of the large follow-on wind turbines.

## Power System Dynamics

Operation of the WT synchronized to the utility network showed two types of power variations. The mean power was found to vary slowly with changes in wind speed and a higher frequency variation about the mean was also observed. A study of the data was initiated to understand the source of the variations and to determine means of reducing them.

Figure 13 shows strip chart data traces of the blade pitch angle, alternator power and wind speed. The variations of the mean power is evident here and occurs as the wind speed increases from 20 to 30 mph. Also the 2P power variation about the mean can be seen in figure 13. The following describes the control and design changes that have been made to the Mod-0 WT to reduce these power variations to acceptable levels. Again, it is noted that operation of the Mod-0 WT has led to an early discovery of potential problems and their solution. This information is also directly applicable to the follow-on large wind turbines.

Variation of Mean Power - Elimination of the varying mean power revealed a problem in the blade pitch control. This control is an integral control that adjusts blade pitch angle to control the alternator power to the selected power set point. Increasing the gain of this control results in instability while reducing the gain results in a very slow responding control. Analysis and tests showed that the addition of proportional control to the system was unsatisfactory, primarily because of the power drive train resonance occurring at less than 1 hz.

To correct this problem it was necessary to go to a feed-forward control using wind speed as the feed forward signal. Figure 14 shows the simple block diagram of this control coupled with the integral control system. Essentially the control performs by sensing wind speed changes on the WT nacelle and using this signal to make blade pitch changes. The closed loop control is still active and controls to the required power setting. The feed forward allows more rapid control to follow wind gust changes. Figure 15 shows a comparison of the power output with and without feed forward control. The feed forward control appears to have reduced the variation of the mean power; this control is still under study.

Variation of Power About the Mean (2P) - The downwind rotor causes a pulse to be put on the power drive train everytime a blade passes through the tower wake. Figure 16 shows the shaft torque as a function of wind speed and blade position. The torque pulse is transmitted through the drive train twice per rotor revolution (2P). Because of the power train dynamics, the magnitude of the torque pulse is amplified by about a factor of 2 at the alternator output.

The power train torque variations can be reduced by (1) reducing the tower shadow or (2) increasing the damping in the power train. Since the tower shadow was already reduced by removing the stairs, it was decided to increase the power train damping. This was done by adding a fluid coupling in the high speed shaft. Figure 17 compares two strip charts with the WT operating with and without a fluid coupling. The data shows that for wind speeds of 30 mph the power oscillations were reduced from $\pm$30 kW to $\pm$12 kW by the fluid coupling. As a result, the power oscillations are not considered to be a problem for utility operation.

## Aerodynamic Performance

The Mod-0 was designed to deliver 100 kW of the alternator output for hub height wind speeds of 18 mph. Figure 7 shows the expected power output versus wind speed.

Tests have been conducted at Plum Brook to determine the Mod-0 performance. The performance of the Mod-0 was determined by using data from the WT, the nacelle anemometer and the meteorological (met) anemometer; figure 18 shows the relative location of this hardware at the Plum Brook site. The alternator power, nacelle wind speed and met tower wind speed data were recorded simultaneously with the wind turbine synchronized to the utility network. Approximately 2 hours of data were taken with wind speeds in the range of 10 mph to 35 mph.

To obtain the WT power versus met tower wind speed, three steps were taken. First, the alternator power was plotted versus nacelle wind speed (see fig. 19a). The scatter in this data is probably due to wind speed and wind direction changes. This data was then averaged over regions of 1 mph to obtain the plot shown in figure 19b. This figure shows a leveling off of the averaged power at less than 100 kW in high winds which was due to a power control set point of 90 kW. It also shows the lack of convergence at the extremes of the wind speed range, which results from having too few data points. Next, the wind shear was calculated from 4 simultaneous readings of the anemometers on the meteorological tower, and this data interpolated to obtain the wind speed for the 100 foot level. The nacelle wind speed was then correlated with the 100 foot wind speed at the meteorological tower. This data was averaged over 2 minute intervals to obtain average nacelle wind speed for an average met tower wind speed. Analysis was performed that showed 2 minutes was sufficient for obtaining correlation between two sites located 650 feet apart. Figure 20 shows the resulting plot of met tower wind speed versus nacelle wind speed. The third step was to cross plot the results of the first two steps to obtain a plot of WT power versus met tower wind speed. This result is shown in figure 21 super-imposed on the plot of predicted performance. The results show that the WT performs better than predicted at these wind speeds. A possible explanation for this result is the fact that the Mod-0 was sized assuming a rough airfoil and the actual airfoil is more like a smooth airfoil.

## CONCLUDING REMARKS

The ERDA/NASA 100 kW Mod-0 was first operated at rated speed and power in December, 1975 in winds of 25-35 mph. These tests showed higher than expected loads, particularly blade loads. As a result, the wind turbine was modified to reduce these loads. These modifications included removing the stairways in the tower to reduce the tower blockage of wind and stiffening the yaw drive system. These modifications resulted in reducing the mean loads to levels below those predicted for the wind turbine by MOSTAB analysis.

General operation of a large wind turbine has been fully demonstrated by the Mod-0. These operations include startup, synchronization to a utility network, blade pitch control for control of power level, and shutdown. Limited wind turbine operations have been demonstrated in a fully automatic mode and by use of a remote control and monitoring panel, 50 miles from the site, similar to what a utility dispatcher would use.

Early operation of the Mod-0 connected to the utility network revealed oscillations in the alternator power output of $\pm30$ kW. The oscillations were due to the reduced torque impulse caused by each blade passing through the tower wake. The oscillations were reduced to less than $\pm12$ kW by adding a commercially available fluid coupling to the high speed shaft.

Aerodynamic performance of the Mod-0 was determined to be better than predicted.

In summary, the Mod-0 wind turbine has been meeting its primary objective of providing the entire wind energy program with early operations and performance data for large wind turbines. The engineering data on dynamic loads, utility operation, aerodynamic performance, etc., has contributed directly to increasing the probability of success for the follow-on large wind turbines. It is planned to continue to use the Mod-0 as a test bed to evaluate wind turbine concepts that show promise for a lower cost.

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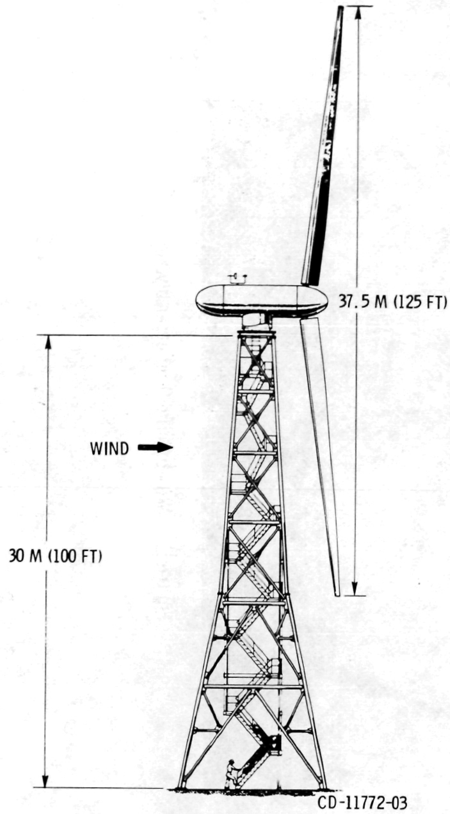


Figure 1. - 100-kilowatt experimental wind turbine.

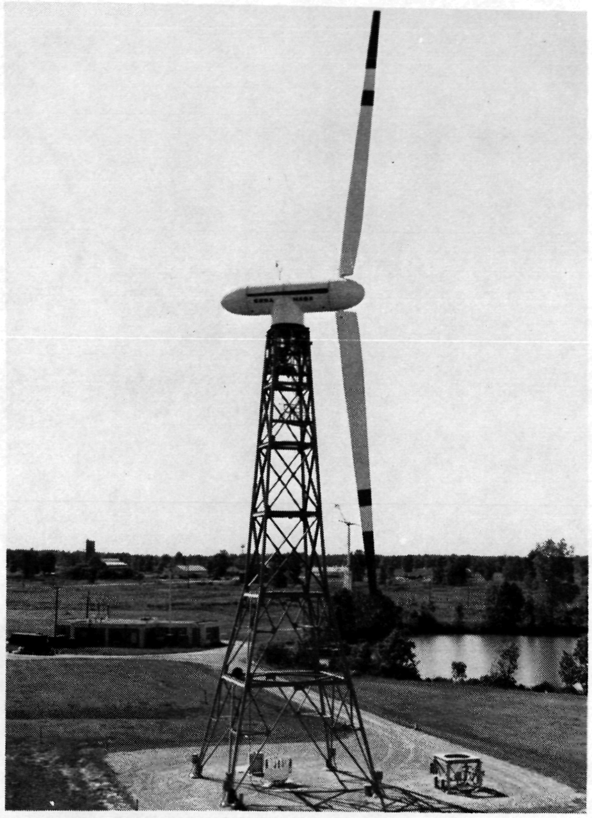

Figure 2. - Photo of 100 kW Mod-0 Wind Turbine.

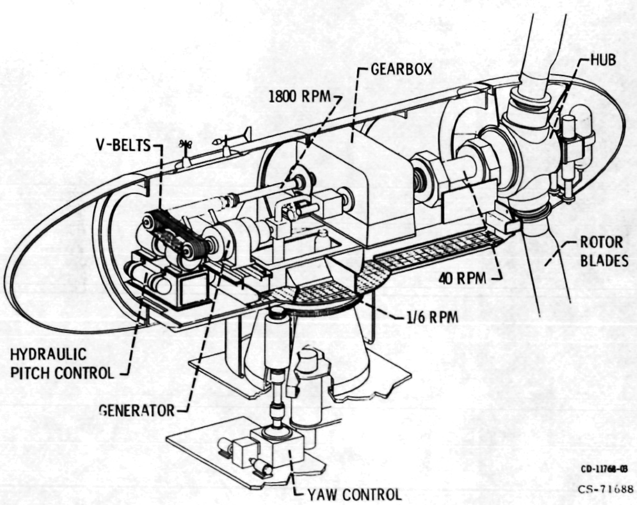


Figure 3. - 100 kW wind turbine drive train assembly and yaw system.

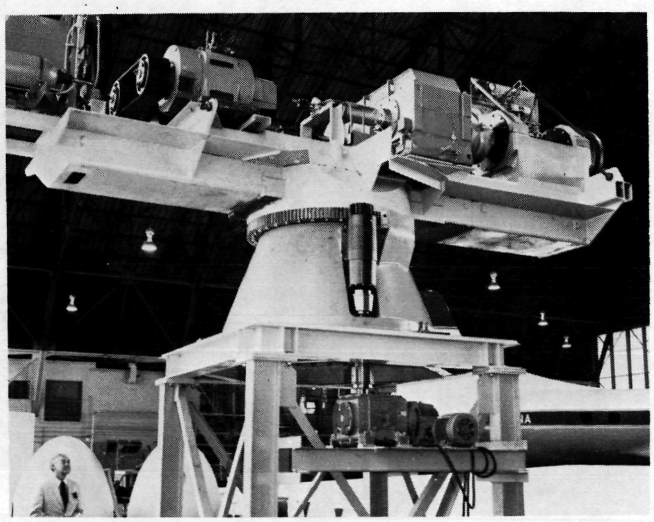

Figure 4a. - Test of drive train and yaw assembly at Lewis Research Center.

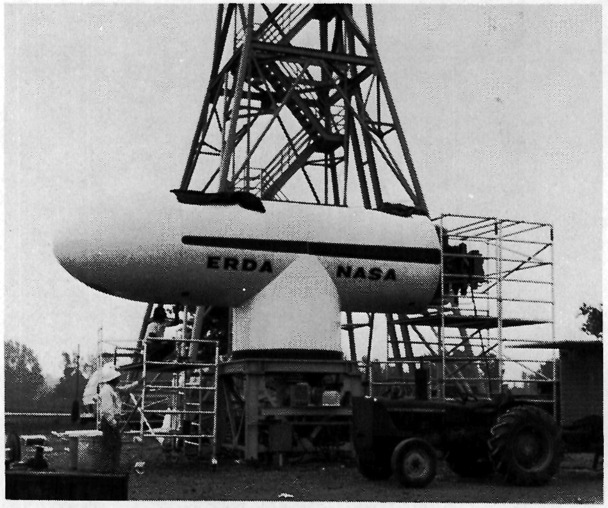


Figure 4b. - Drive train and yaw assembly at Plum Brook.

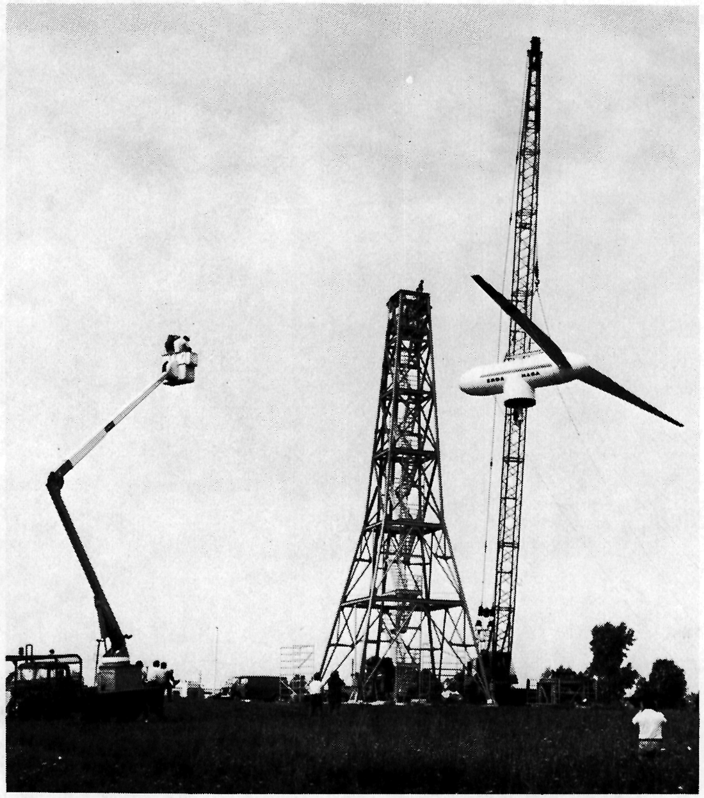

Figure 5. - Wind turbine final assembly.

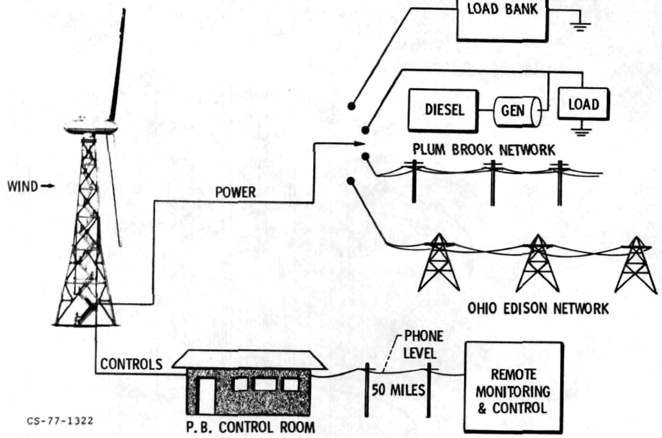


Figure 6. - Mod-0 operation.

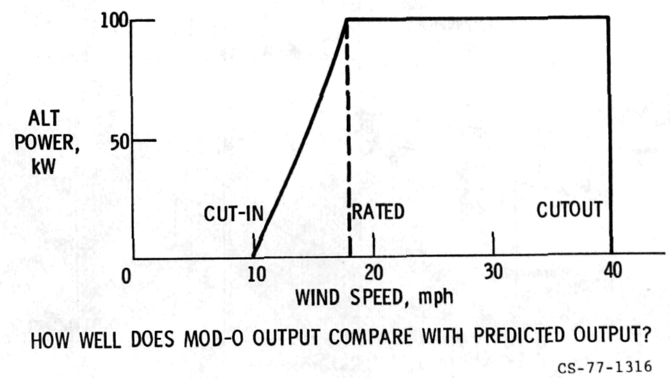


Figure 7. - Mod-0 operation: power vs. wind speed.

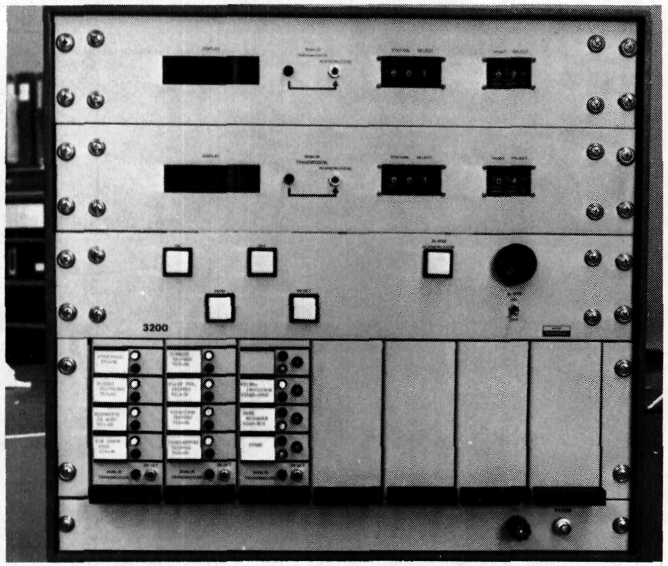


Figure 8. - Remote control and monitoring system.

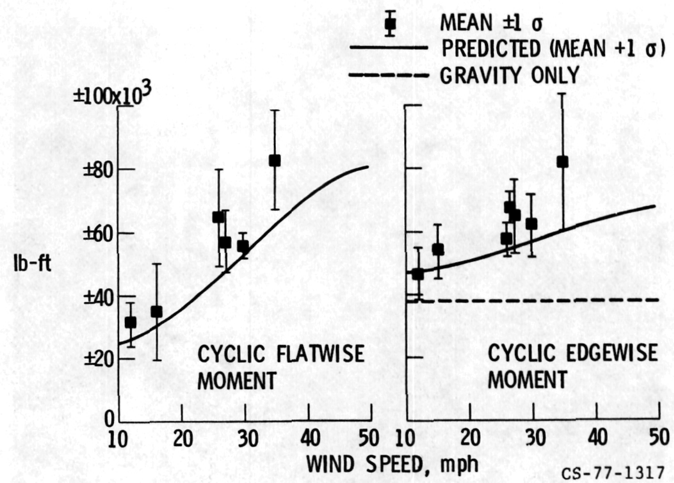


Figure 9. - Mod-0 blade loads.

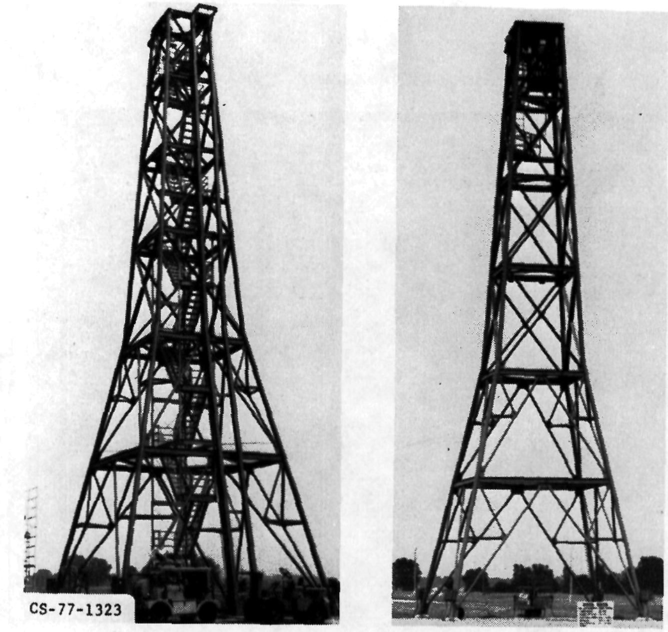


Figure 10. - Mod-0 tower with and without stairs.

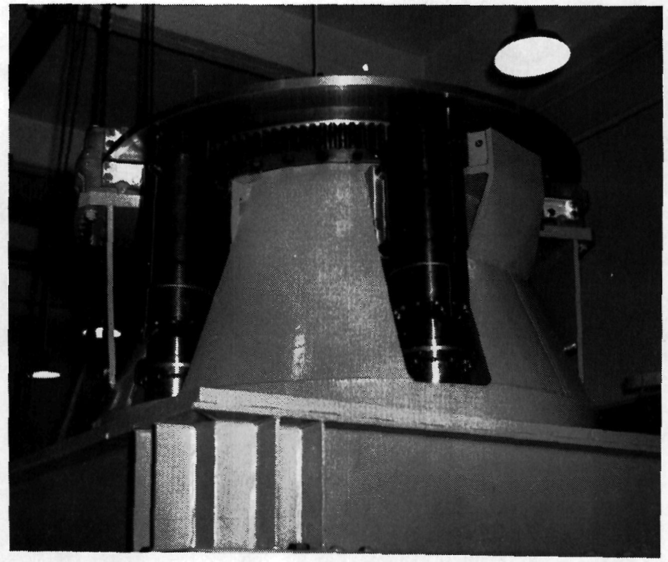

Figure 11b. - Mod-0 dual yaw system with yaw brakes.

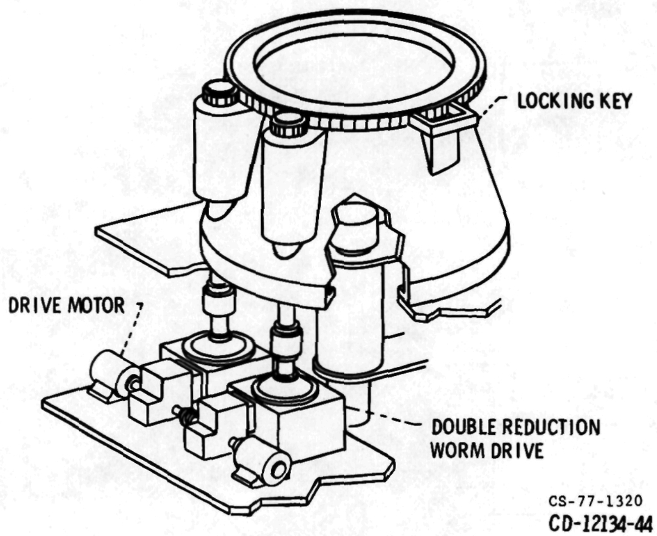


Figure 11a. - Mod-0 dual yaw drive system.

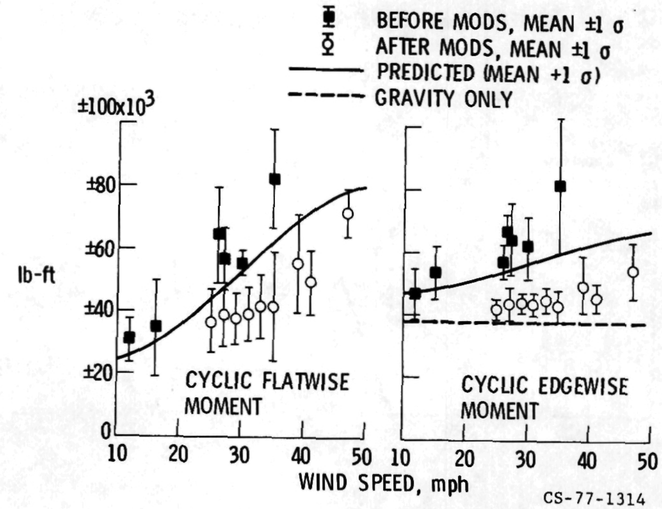


Figure 12. - Mod-0 blade loads before and after modifications.

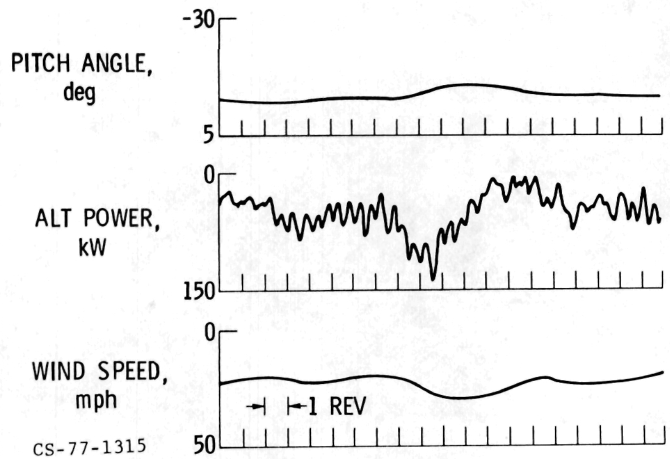


Figure 13. - Power system dynamics.

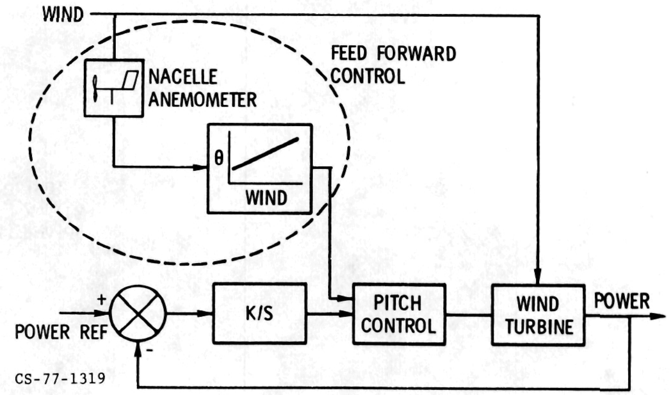


Figure 14. - Mod-0 power control system.

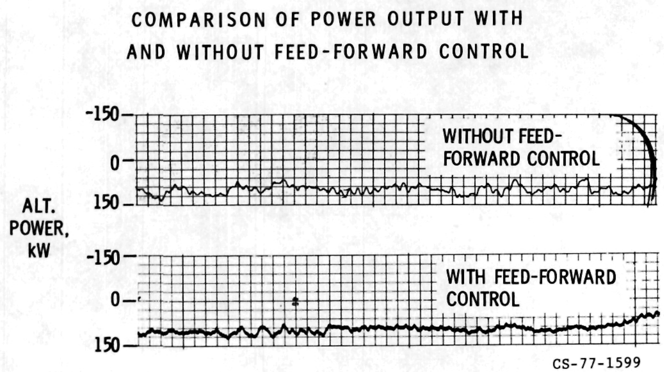


Figure 15.

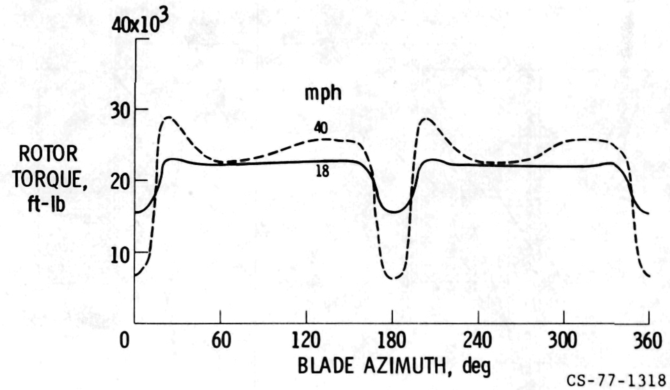


Figure 16. - Mod-0 prediction: rotor torque vs. blade azimuth.

COMPARISON OF POWER OSCILLATIONS WITH AND WITHOUT HYDRAULIC COUPLING

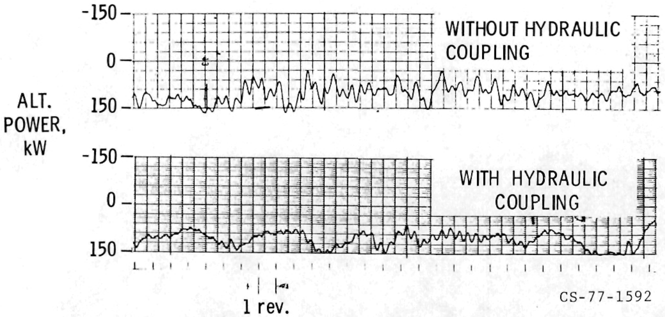


Figure 17.

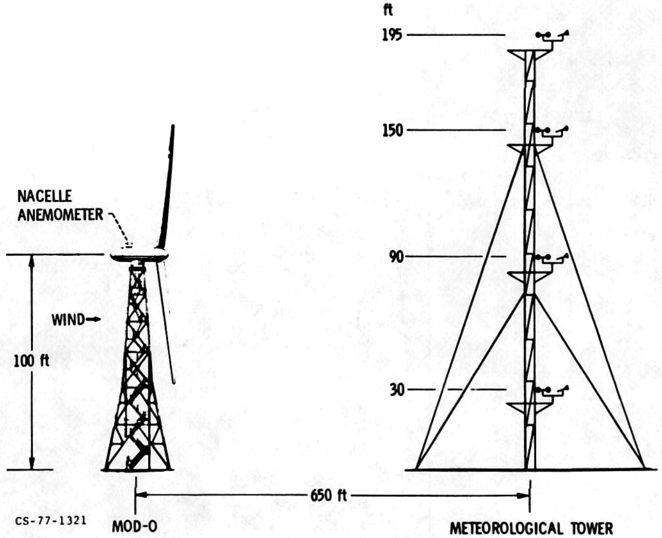


Figure 18. - Mod-0 performance: instrumentation layout.

MOD-0 PERFORMANCE: POWER VS. NACELLE WIND SPEED

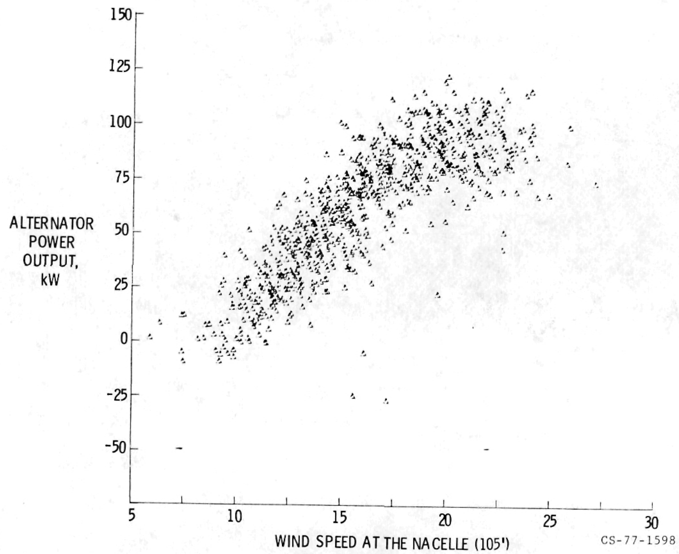


Figure 19a.

MOD-0 PERFORMANCE:

REGION AVERAGED POWER VS. NACELLE WIND SPEED

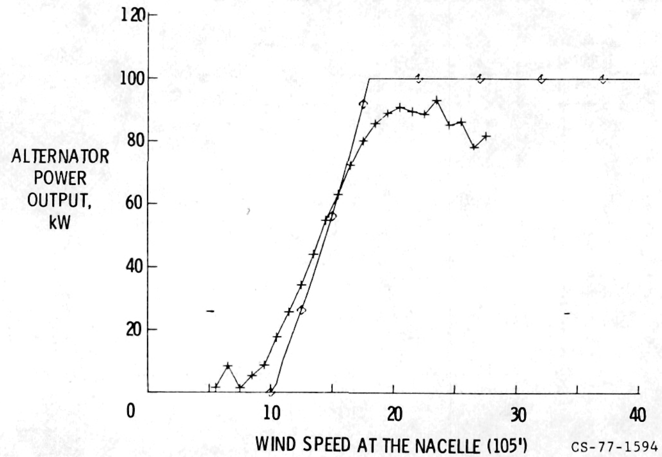


Figure 19b.

MOD-0 PERFORMANCE: MET. TOWER VS. NACELLE WIND SPEED

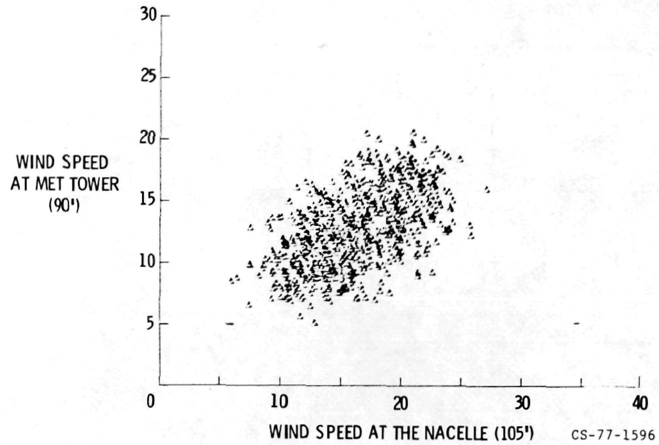


Figure 20a.

MOD-0 PERFORMANCE: 2-MINUTE AVERAGES OF MET. TOWER VS. NACELLE WIND SPEED

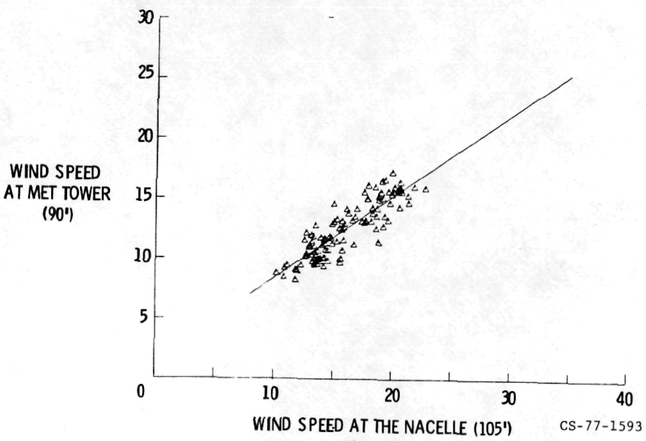


Figure 20b.

MOD-0 PERFORMANCE:

CROSSPLOTTED POWER VS. MET. TOWER WIND SPEED

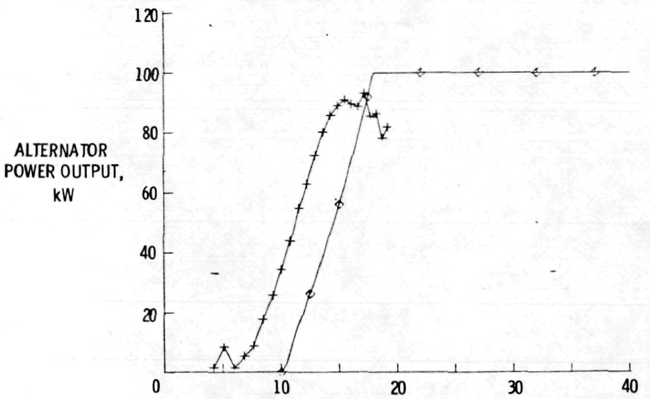


Figure 21.

~~G. Fuchs 241/1/24061~~

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